Effect of Build Parameters on the Strength of FDM Parts

U VAMSI AVINASH

A Dissertation Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

Indian Institute of Technology Hyderabad

Department of Mechanical and Aerospace Engineering

June, 2014

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(Signature)

U V Avinash
(Student Name)

ME12M1027
(Roll No)

Approval Sheet

This thesis entitled "Effect of Build Parameters on the Strength of FDM Parts" by U V Avinash is approved for the degree of Master of Technology from IIT Hyderabad.

Dr. S Surya Kumar
Department of Mechanical and Aerospace Engineering
IIT Hyderabad
Adviser

Dr. N Venkata Reddy
Department of Mechanical and Aerospace Engineering
IIT Hyderabad
Internal Examiner

30/6/2014
Dr. A Venugopal Rao
DMRL
Hyderabad
External Examiner

Dr. Manish K Niranjan
Department of Physics
IIT Hyderabad
Chairman

Acknowledgments

I would like to express my sincere thanks to my adviser **Dr. S Surya Kumar** for his constant support throughout my thesis work. His logical way of thinking and enthusiastic support motivated me a lot to do this project. The discussions that I had with him were a major source of learning and improving my knowledge and communication skills. His guidance helped me in all the time during the project.

I would like to thank Department of Mechanical and Aerospace Engineering, IIT Hyderabad for providing all the necessary facilities during the research work.

I would like to thank **M.A.Somasekhara** (PhD Scholar) for his cooperation and generous help throughout my project. I would like to thank **Moulali Syed** and **Dhananjay Sahoo** for helping me in the manufacturing and metrology lab. I would like to thank **K.Naresh Reddy** for helping me out in conducting experiments on tensile specimens in Engineering Optics lab.

I would like to express my heartfelt thanks to all my classmates and my friends for giving me the moral support.

ABSTRACT

Fused Deposition Modeling (FDM) is one of the popular Additive Manufacturing (AM) processes that can provide functional prototypes of Acrylonitrile butadiene styrene (ABS) plastic. As AM processes build the component in a layer-by-layer manner, they tend to be anisotropic in nature. The fill pattern and process parameters can affect the strength of parts produced in AM. Hence, a study of effect of process parameters like fill density, fill pattern, orientation etc on the mechanical properties was felt necessary. This work presents the results of different types of ABS components fabricated while varying the process parameters and their effect of mechanical strength of component. Young’s modulus and ultimate strength were used for the same. The results will help the user in identifying the right process parameters for a desired object.

CONTENT

1. INTRODUCTION

1.1 Additive manufacturing

Additive manufacturing (AM) refers to a group of solid freeform fabrication (SFF) processes that are capable of developing complex shapes without part-specific tooling in a short span of time. New AM processes are being developed and commercialized. There are number of automated machines or processes like Stereo Lithography (SL), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Photo-Masking or Solid Ground Curing, Three Dimension printing etc. which fabricate three dimensional (3D) solid models from CAD data automatically without the use of specific shape tool and minimum human intervention.

The following five-step process is common to all various AM:

1. Create a CAD model of the design

2. Convert the CAD model to STL format

3. Slice the STL file into thin cross-sectional layers

4. Construct the model one layer atop another

5. Post processing

1.1.1 Creating a CAD model: Firstly, the object to be built is modelled using a Computer-Aided Design (CAD) software package. Solid modellers, such as Pro/ENGINEER, Unigraphics, Catia etc., tend to represent 3-D objects more accurately than wire-frame modellers such as Auto-CAD and will therefore yield better results.

1.1.2 Conversion to STL Format: The various CAD packages use a number of different algorithms to represent solid objects. To establish consistency, the STL (stereo lithography), format has been adopted as the standard of the AM industry. The second step, therefore, is to convert the CAD file into STL format. This format represents a three-dimensional surface as an assembly of planar triangles, “like the facets of a cut jewel”. The file contains the coordinates of the vertices and the direction of the outward normal of each triangle. Because STL files use planar elements, they cannot represent curved surfaces exactly. Increasing the number of triangles improves the approximation, but at the cost of bigger files size. Large, complicated files require more time to pre-process and build, so the designer must balance accuracy with manageability to produce a useful STL file. Since, the .stl format is universal; this process is identical for all of the AM build techniques.

1.1.3 Slice the STL File: In the third step, a pre-processing program prepares the STL file to be built. Several programs are available, and mostly allow the user to adjust the size, location and orientation of the model. Build orientation is important for several reasons. First, properties of rapid prototypes vary from one coordinate direction to another. For example, prototypes are usually weaker and less accurate in the z (vertical) direction than in the x-y plane. In addition, part orientation partially determines the amount of time required to build the model. Placing the shortest dimension in the z direction reduces the number of layers, there by shortening build time.

The pre-processing software slices the STL model into a number of layers depending on the build technique. The program may also generate an auxiliary structure to support the model during the build. Supports are useful for delicate features such as overhangs, internal cavities, and thin-walled sections. Mostly, each RP machine manufacturer supplies their pre-processing software.

1.1.4 Layer by Layer Construction: The fourth step is the actual construction of the part. Using one of several techniques RP machines build one layer at a time from polymers, paper, or powdered metal. In FDM, molten material comes out of a nozzle, falls on the base material and solidifies. The material comes out in the form of a fluid rope, takes the desired shape and solidifies in a manner similar to making noodles. Molten material inside a hot chamber is extruded through a nozzle. Most machines are fairly autonomous, needing little human intervention.

1.1.5 Post Processing: The final step is post-processing. This involves removing the prototype from the machine and detaching any supports. Some photosensitive materials need to be fully cured before use. Prototypes may also require minor cleaning and surface treatment. Sanding, sealing, and/or painting the model will improve its appearance and durability.

1.2 Fused Deposition Modeling (FDM)

By far the most common extrusion-based AM technology is Fused Deposition Modeling (FDM), developed by Stratasys, USA. FDM uses a heating chamber to liquefy the polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure. The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using this technology. Parts made using FDM are amongst the strongest for any polymer-based additive manufacturing process.

The main drawback of using this technology is the build speed. As mentioned earlier, the inertia of the plotting heads means that the maximum speeds and accelerations that can be obtained are somewhat smaller than other systems. Furthermore, FDM requires material to be plotted in a point-wise, vector fashion that involves many changes in direction.

The machine has a XY table at the top. The XY table carries a twin-extrusion head which it can be moved in the XY plane along the desired path at the desired speed. The XY table and the platform are inside an insulated cabin whose temperature is to be maintained by the heating coils. The user can set the required temperature depending on the material used for extrusion. Generally the temperature is set a little above the melting point of the material. During the extrusion, a stream of thin filament of the semisolid material comes out of the nozzle. Its diameter is same as that of that of nozzle. Any layer is obtained by depositing the filament along its contours and filling the interiors of these contours by this filament in a zig-zag fashion similar to metal cladding using a welding gun. As the material is deposited on the platform, the platform lowers and the deposition continues on the previous layer. This process continues till the model is created. The schematic of FDM is shown in the figure 1.1. The following are some of advantages and disadvantages of this process:

1.2.1 Advantages:

1) Machine cost is less,
2) Ease of operation,
3) Post curing is not required.

1.2.2 Disadvantages:

1) Accuracy and surface finish is less,
2) Strength is low in Z-direction.

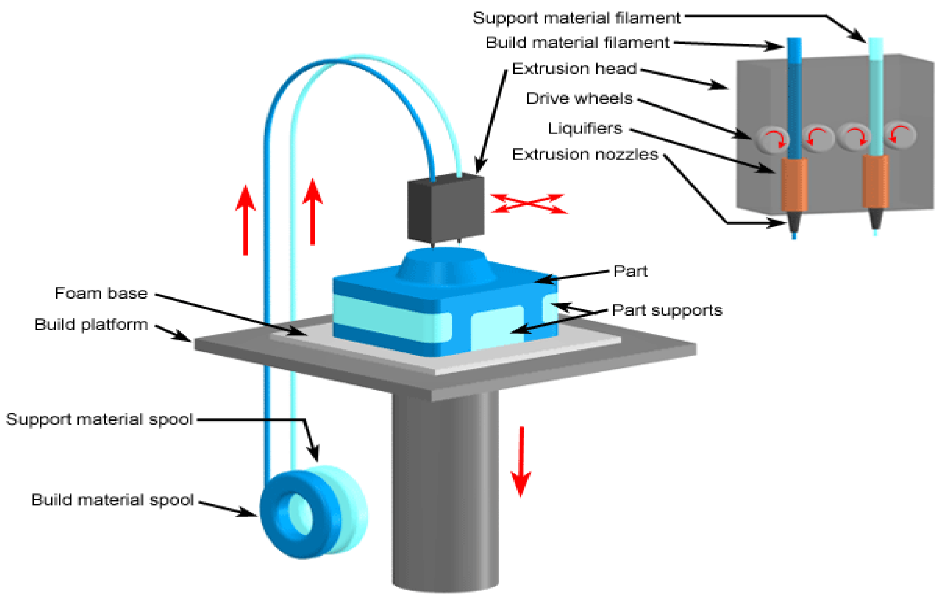


Figure 1.1: Fused Deposition Modeling [1]

[http://www.custompartnet.com/wu/fused-deposition-modeling]

2. LITERATURE SURVEY

2.1 Earlier Studies on FDM Process Parameters

Owing to simplicity and comparative affordability and the ability to create strong polymers, FDM has been of considerable research interest. Hossain et.al., [2] studied the tensile mechanical properties of specimens built using three sets of parameters. They studied effect of processing parameters like build orientation, raster angle (RA), contour width (CW), number of contours, raster width (RW), raster to contour air gap, raster to raster air gap (RRAG) and slice height.

The build orientation is the orientation of the part with respect to build platform. RA is the angle created between the raster and the positive X direction of the build platform. CW and RW are the width of contour and raster, respectively. RRAG is the distance between the edges of two adjacent rasters. A negative RRAG (obtained by decreasing RRAG from zero) causes the partial overlap between two adjacent rasters, as shown in Figure 2.1.

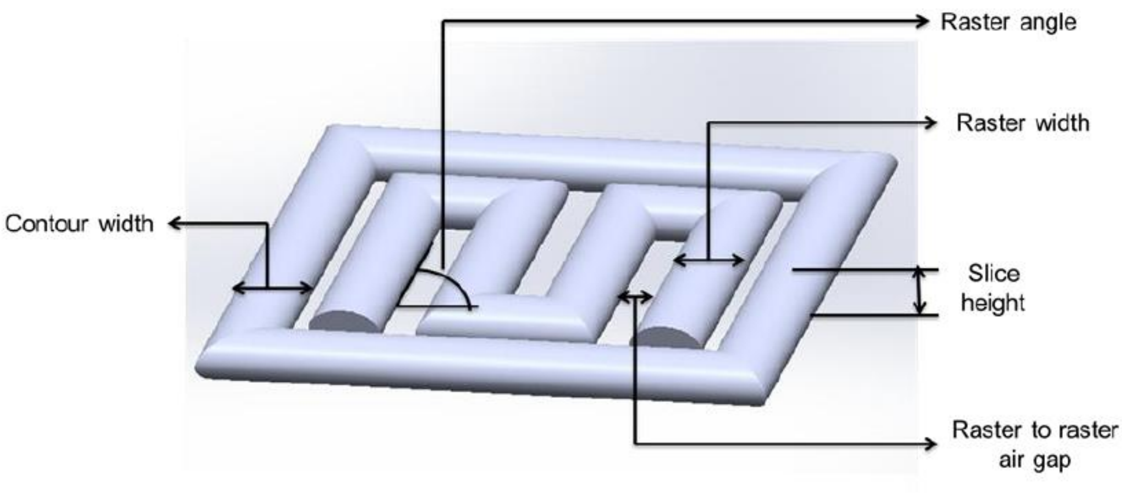


Figure 2.1: FDM Build Parameters

This study concluded that parameter modification using Insight revision method, improved the Ultimate Tensile Strength (UTS) compared to default values. The visual feedback method further improved UTS, introducing negative RRAGs, which led to an average increase in UTS of 16 % compared to the specimens built with default parameters. Overall, the highest average value of UTS obtained for PC was 53.75 Mpa (compared to 46.84 MPa with the default).

Chakraborthy et.al., [3] studied a new rapid prototyping technique named curved layer fused deposition modeling (CLFDM) in extruder path generation. These studies would be particularly advantageous over FDM in the manufacturing of thin, curved parts (shells) by reduction of stair-step effect, increase in strength and reduction in the number of layers. Studies concluded that higher strength is obtainable by employing longer length filaments or roads and obtaining curved inter-layers of larger area per layer. However, disadvantage from this process is capital investments would increase due to the requirement of higher sophistication in part and extruder manipulation.

Anitha et.al., [4] employed using taguchi technique to study the influence of different parameters on the quality of prototypes. They concluded that without pooling, layer thickness is effective to 49.37% (at 95% level of significance) and with pooling the layer thickness is effective to 51.57% (at 99% level of significance). The significance of layer thickness is further strengthened by the correlation analysis, which indicates a strong inverse relationship with surface roughness.

Galantucci et.al., [5] studied the influence of FDM parameters on acrylonitrile butadiene styrene (ABS) prototypes surface finish. The slice height and the raster width are important parameters while the tip diameter has little importance for surfaces running either parallel or perpendicular to the build direction. A chemical post-processing treatment has been analyzed and yields a significant improvement of the R_a of the treated specimens.

Pandey et.al., [6] studied the part deposition orientation in as it effects build time, support structure, dimensional accuracy etc. It is a difficult and time consuming task as one has to trade-off among various contradicting objectives like surface finish and build-time. This work helped in developing an optimal part deposition orientation system based on actual surface profile characteristics for different AM processes by considering various objectives in which all possible orientations are investigated unlike few preselected orientations.

Rattanawong et.al., [7] studied a methodology for computing the volumetric error for any orientation of the parts built by the fused deposition modeling system. The technique can be applied to determine the best orientation of the part, based on the minimum volumetric error. The methodology has been shown to work for various primitive volumes and for simple parts made from the primitives such as cylinders, cubes, spheres and pyramids. This procedure has also been verified experimentally for parts built on the FDM rapid prototyping system.

Thrimurthulu et.al., [8] studied on obtaining an optimum part deposition orientation for FDM process in enhancing part surface finish and reducing build time. A real coded genetic algorithm is used to obtain the optimum solution. Studies concluded that the proposed methodology can be used to determine optimum part deposition orientation for any complex part that may be completely freeform.

Phatak et.al., [9] studied the part orientation in RP process, as it directly governs productivity, part quality and cost of manufacturing. Genetic algorithm based strategy was used to obtain optimum orientation of the parts for RP process. The objective criteria for optimization is considered to be a weighted average of the performance measures such as build time, part quality and the material used in the hollowed model. The developed system has been tested with several case studies with SLS process. A modular system was also designed and implemented by Phatak et.al., to find the optimum orientation of the CAD part model using genetic algorithm technique. The system produces optimum orientation of part to minimize build time, staircase error and material used as per the requirements of the user. Studies indicate that the modified CAD part models will provide significant improvements in productivity, part quality and economy during the part manufacture.

Alexander et.al., [10] studied the determination of best build orientation and minimizing build cost of a part in any laminated manufacturing (LM) process. Although determining the best orientation of a part may be considered simple, it has been shown that even for some of these parts the ‘obvious’ orientation may not necessarily be the best. For complex geometries, where an orientation is not immediately obvious, the best orientation can easily be determined using the Orientation module (ORM) without operator intervention.

Sreeram et.al., [11] studied adaptive slicing algorithm that uses cusp height as the tolerance criterion. In this algorithm, all vertices in the model are first sorted according to their projection value in the building direction. The model is separated into sections based on the projection values, so that the enclosed part between sections is continuous in geometry. The layer thickness is adaptively computed from the beginning of each section based on the given tolerance and the angle at which the surface normal vector intersects with the building direction vector. Here, the adaptive slicing of polyhedral objects was discussed.

Lee et.al., [12] studied the mechanical properties of parts produced by RP processes. FDM process is characterized by process parameters such as raster orientation, air gap, bead width, model temperature etc. Specimens were fabricated to measure compressive strengths of the three RP processes and most of them showed anisotropic compressive properties. From the compression test, it was confirmed that build direction was important process parameter that affects mechanical properties. In addition, it was found that parts made by 3D printer had low compressive strength compared to other processes, and that FDM parts had high compressive strength.

Mani et.al., [13] studied the region-based adaptive slicing. In region-based adaptive slicing, user has the flexibility to impose different surface finish requirements on different surfaces of the model whereas in traditional adaptive slicing the user can impose a single surface finish (cusp height) requirement for the whole object. Two sample models were sliced using the algorithm and fabricated using the Stratasys 3D modeler. In general, this slicing procedure is likely to yield better results for the manufacture of large complex parts which have surface finish requirements only on few critical surfaces.

Ahn et.al., [14] studied the properties of ABS parts fabricated by the FDM 1650. Using a Design of Experiment (DOE) approach, the process parameters of FDM, such as raster orientation, air gap, bead width, color, and model temperature were examined. Tensile strengths and compressive strengths of directionally fabricated specimens were measured and compared with injection moulded FDM ABS P400 material. From the Design of Experiment, it was found that the air gap and raster orientation affect the tensile strength of an FDM part greatly. Bead width, model temperature, and color have little effect. The measured material properties showed that parts made by FDM have anisotropic characteristics. The following build rules were obtained by the authors from this study.
By applying these build rules, the strength and quality of FDM parts can be improved.

1) Build parts such that tensile loads will be carried axially along the fibers.
2) Be aware that stress concentrations occur at radiused corners. This is because the FDM roads exhibit discontinuities at such transitions.
3) Use a negative air gap to increase both strength and stiffness.
4) Consider the effect of build orientation on part accuracy.
5) Be aware that tensile loaded area tends to fail easier than compression loaded area.

Anna et.al., [15] studied methodology of the mechanical characterization of products fabricated using fused deposition modeling. As a consequence of layer-by-layer approach of AM, the parts produced are orthotropic. It has been observed that road shape and the road to road interaction, as well as the path, strongly affects the properties and performance of the finished product. It can be said that the mechanical properties of the final parts considerably depend on two important modeling phases,

a) The chosen building direction, thus the orientation of the object with respect to the substrate,
b) The chosen path, thus the way every layer is filled by roads.

Pandey et.al., [16] studied the slicing procedure in fused deposition modelling, based on real time edge profile of deposited layers. An approach for adaptive slicing based on the realistic build edge profile is implemented using two approaches, namely direct slicing and tessellated model (STL). In comparison to earlier approaches of adaptive slicing based on cusp height and area deviation using the rectangular build edge profiles, it can be easily seen that the present methodology can reduce the number of slices, and hence build time. The major advantage of the present methodology is that the part quality is expressed in terms of standard R_a value which is used in design and manufacturing. Their studies concluded that for most of the AM processes, the surface roughness is proportional to layer height.

Masood et.al., [17] studied a generic mathematical algorithm to determine the best part orientation for building a part in a AM system. The algorithm works on the principle of computing the volumetric error (VE) in a part at different orientations and then determining the best orientation based on the minimum VE in the part. The part orientation system based on this algorithm graphically displays the VE at different part orientations and recommends the best part orientation. The system allows the part to be orientated in space by manipulation of rotation about any of the three axes individually or by rotation with a combination of two axes. The algorithm has been verified experimentally and mathematically by considering the VEs in primitive shapes and by actual parts built on the AM system. Their studies concluded that part orientation system developed with this algorithm will provide the AM user to make a better decision in fabricating AM parts with higher degree of accuracy and surface finish.

Rezaie et.al., [18] studied the issues and opportunities for the application of topology optimization methods for AM. Converting topology optimization output files to usable AM input data for production of meso-scale structures for realizing intermediated density regions are investigated. This methodology is then implemented for the fused deposition modeling process (FDM). Their studies concluded that by applying the proposed methodology, a topology optimized part can be fabricated by a low cost FDM apparatus with as little as sacrificing the features obtained from the optimization stage.

Galantucci et.al., [19] studied on surface finish of FDM parts which can be improved by performing chemical dipping based on immersion in a dimethylketone–water solution. They tried to gain a more in-depth knowledge of this process, by analyzing and comparing the mechanical properties and the surface quality of treated and untreated FDM parts. The mechanical properties of FDM prototypes treated with a solution of 90% dimethylketone and 10% water have been analyzed. The treatment can be used to dramatically improve the surface finish of ABS prototypes.

Anoop et.al., [20] studied the effect of five important parameters such as layer thickness, part build orientation, raster angle, raster width and air gap on the compressive stress of test specimen. The study not only provides insight into complex dependency of compressive stress on process parameters but also develops a statistically validated predictive equation. The equation is used to find optimal parameter setting through quantum-behaved particle swarm optimization (QPSO).

As FDM process is a highly complex one and process parameters influence the responses in a non linear manner, compressive stress is predicted using artificial neural network (ANN) and is compared with predictive equation. The developed relationship between compressive stress (output) and process parameters (input) is able to explain the 96.13% of variability in the response and is suitable to explore the design space for future engineering applications. Effect of various factors and their interactions are explained using response surface plots. In general, it can be said that fibre–fibre bond strength must be strong which can be achieved by controlling the distortions arising during part build stage. The reason of low strength is also due to anisotropy, caused by the polymer molecules aligning themselves with the direction of flow when they are extruded through the head nozzle. The anisotropy can also be caused by the formation of pores in preferred orientations and weak interlayer bonding.

Sarat et.al., [21] studied the curved layer deposition for FDM, in particular for thin shell-like parts, to ensure fibre continuity. Mathematical models are developed for curved slicing, implemented in a few case studies, parts are printed, and test results suggest marked improvement in the mechanical characteristics of curved layer parts. Algorithms for curved layer slicing are developed based on practical solutions. Application of the algorithms in different cases of varying geometrical complexity proved the models to be effective. CLFDM is successfully implemented and physical parts are generated using both fabepoxy and ABS polymer. Experimental results indicate better mechanical performance by parts produced using curved layer FDM.

2.2 Motivation for the present work: As may be deduced from the above discussions, the properties of FDM parts are different in different directions. The process parameters and orientation factor play an important role in deciding the characteristics of the build part like surface roughness, time of manufacture, material utilization, mechanical strength etc. Earlier research has focussed on varying the orientation, model densities, process parameters etc. on surface roughness and built time. However, a deeper study on the effect of these parameters on the mechanical strength was found lacking. The present work, with the help of experiments, concentrates on studying the effect of fill parameters on the mechanical strength of the FDM parts.

3. STUDY OF CONTROL PARAMETERS

3.1 Introduction

Control parameters play an important role in building a part. These are used to find the optimal parameters for a desired product. This can be achieved by varying the different parameters options available in the machine and the software. The present chapter presents the work done to understand the role of each of these options.

3.2 3D Printer

FDM is now a crowded space with lot of manufacturers making AM machines based on that technology; 3D printing market are Stratasys, MakerBot, 3D systems, Ultimaker, ZCorp etc are some of the popular manufacturers of the same. Although Stratasys was the first to introduce FDM technology, owing to its simplicity, this spectrum has seen a lot of activity on low end and make-it-yourself FDM machines. The RepRap open source community, thingiverse CAD library from MakerBot etc are some examples of active research by a crowd sourcing model. The current work uses a RepRap machine (Figure 3.1) assembled by Aha! Gadgets due to its flexibility in controlling the process parameters. The following are its specifications:

a) Manufacturer: Aha gadgets
b) Model: R3D2
c) Filament: ABS 1.7 mm
d) Nozzle temperature: 210 ^{0}C
e) Bed temperature: 60 ^{0}C
f) Stepper motor: Used to extrude the filament

Experiments were conducted to understand the effect of process parameters of RepRap machine. Some initial experimental trails were performed on RepRap machine to know the operating range of parameters.

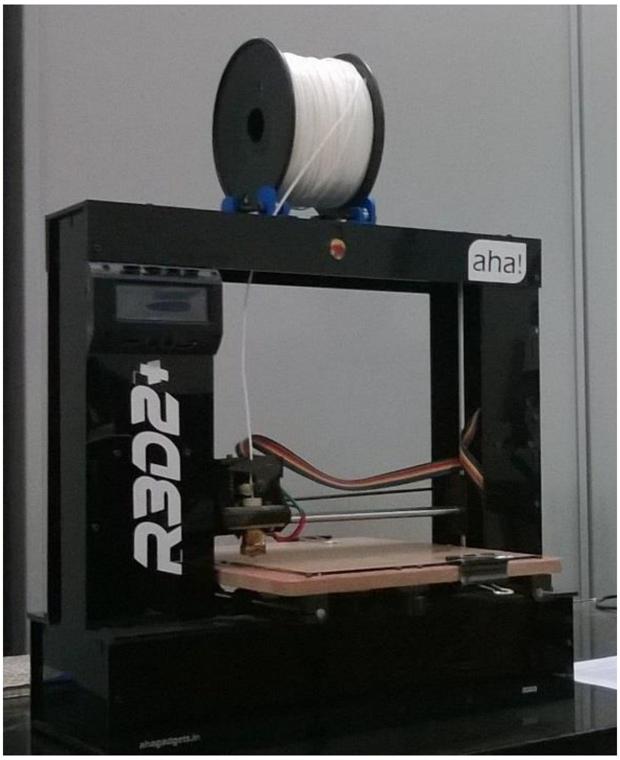


Figure 3.1: 3D Printer Setup at IITH

3.3 Software

A 3D printer cannot cope directly with files from a CAD program. So, 3D or CAD files need to be processed before they become printable and this process is called as slicing and area filling. Hence, the slicing (software) is the first tool we use for 3D printing.

A slicer commonly uses STL files to create the tool paths, usually in Gcode format. These files contain instructions for the 3D printer on where, when, and how fast to make movements. The slicer software slices the STL model into layers and print paths to create a 3D printable Gcode file. There are several slicing programs available, some of them being:

1) Kisslicer
2) Slic3r
3) Skeinforge
4) Repsnapper
5) Netfabb studio

6) Magics etc.

Amongst these, Slic3r software was found most suited for the following reasons:

a) Supports multi-model printing
b) Can split and saves STL files
c) Can handle big STL files
d) Compatible with several hosting programs
e) Works stand-alone
f) Free and open source

Some of the options available in this software are elaborated in the following subsections (Figure 3.2):

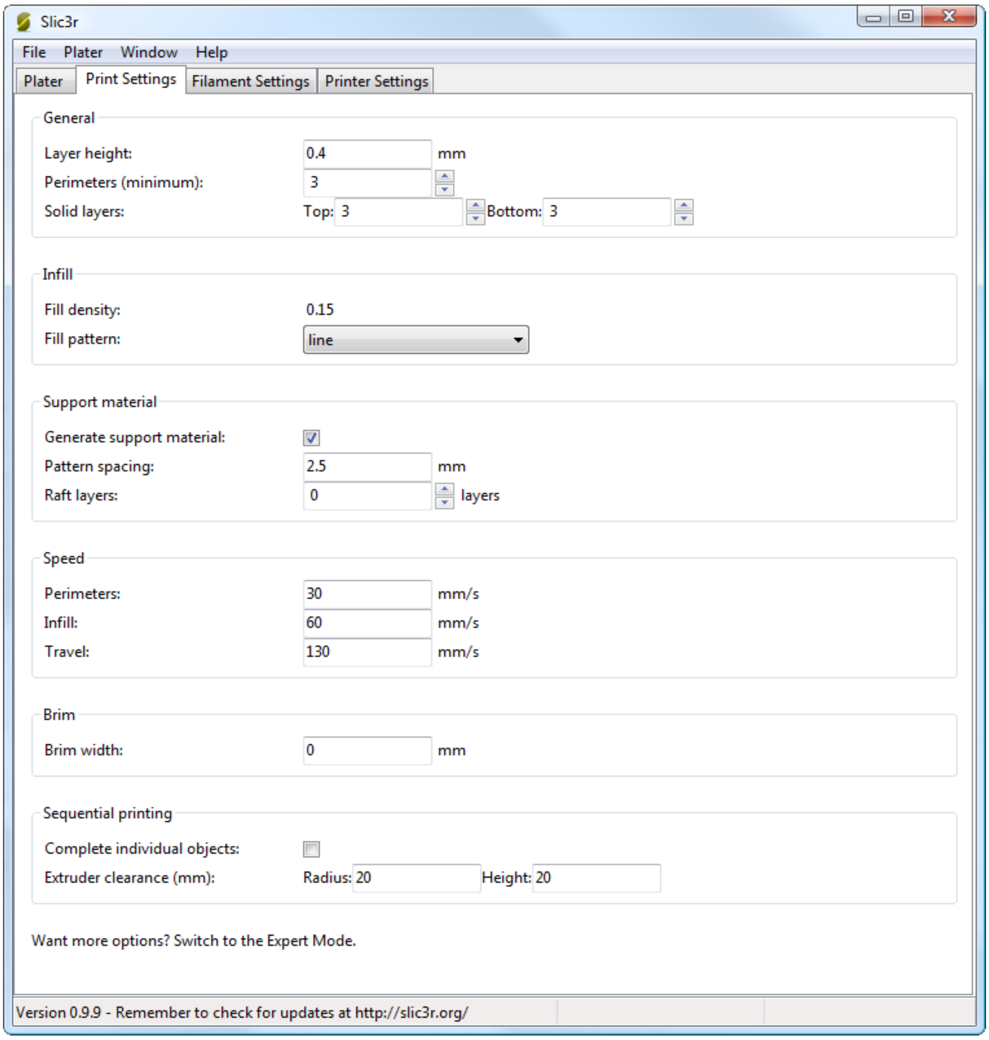


Figure 3.2: Parameter menu of slic3r software

3.3.1 Layer height: It is the thickness (Figure 3.3) of each layer, and it is the step along the vertical axis taken before extruding a new layer atop the previous layer. Shorter layers will result in smoother prints but each print will take longer, simply because the extruder must trace the pattern more times.

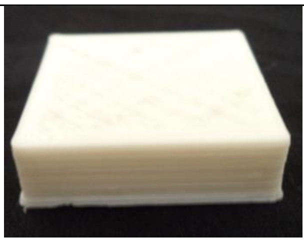
		
Layer height=0.3	Layer height=0.4	Layer height=0.5

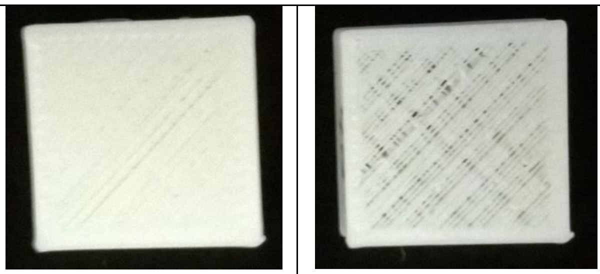
Figure 3.3: Parts with varying Layer thickness

3.3.2 Perimeters: It is the minimum number of vertical shells (Figure 3.4) a print will have. Unless the model requires single width walls it is generally recommended to have a minimum of two perimeters as this gives some insurance that if a section of the perimeter is not printed correctly then the second perimeter will help cover it.

		
Perimeter=8	Perimeter=12	Perimeter=15

Figure 3.4: Parts with varying Perimeter

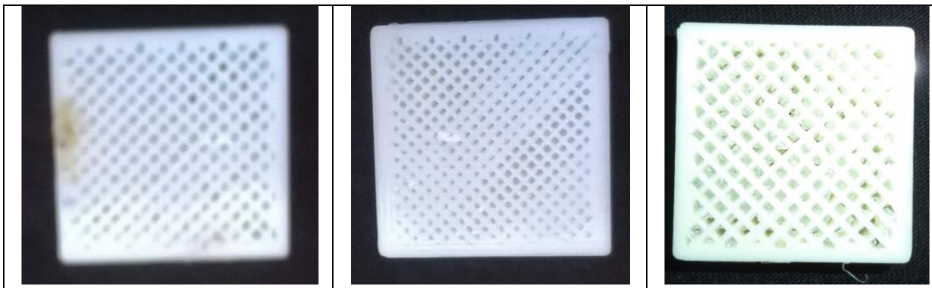
3.3.3 Solid layers: The upper and lower most layers of the model are called as solid layers (Figure 3.5).



Upper layer = 6	Upper layer = 3

Figure 3.5: Parts with varying solid layers

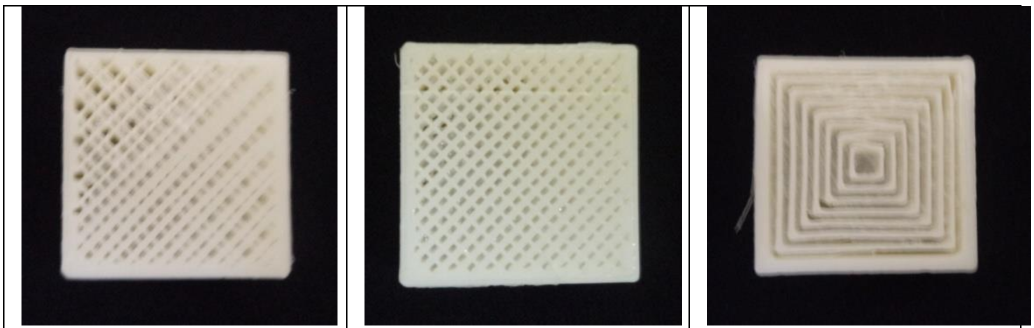
3.3.4 Fill density: It is defined on a scale of between 0 and 1, where 1 is 100% and 0.4 would be 40%. For the majority of cases it makes no sense to 100% fill the model with plastic, this would be a waste of material and take a long time. Instead, most models can be filled with less material which is then sandwiched between layers filled at 100 %.



Fill density = 0.35	Fill density =0.45	Fill density = 0.30

Figure 3.6: Parts with varying Fill density

3.3.5 Fill Patterns: Figure 3.7 shows the different fill patterns deposited,



(a)	(b)	(c)

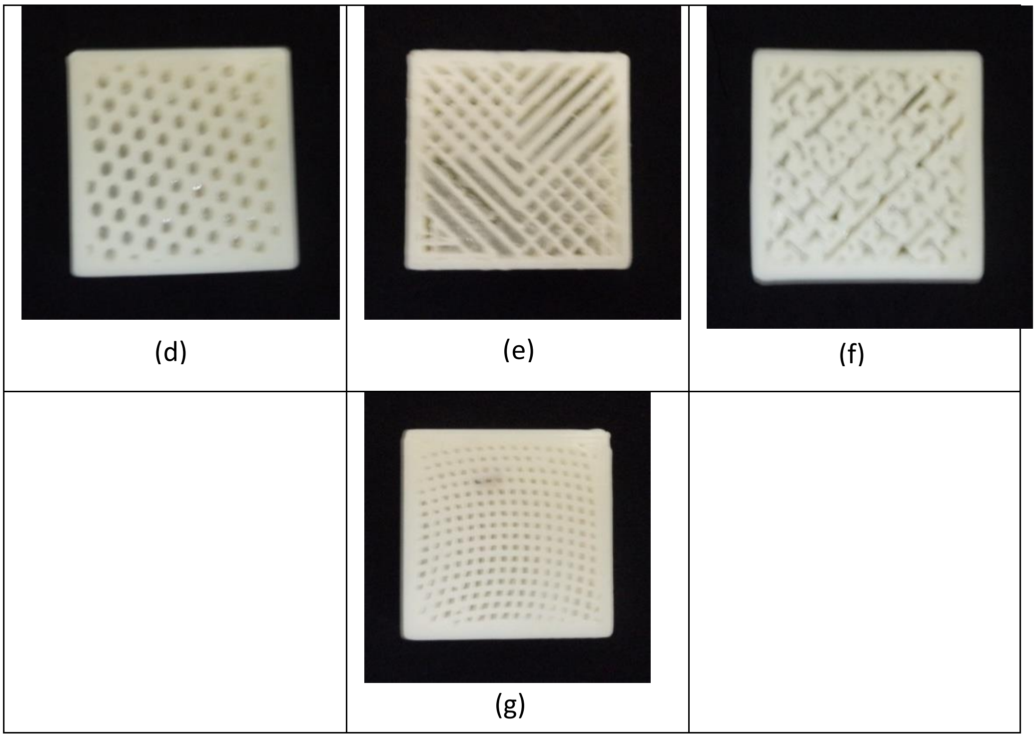


Figure 3.7: Fill patterns: (a) Rectilinear (b) Line (c) Concentric (d) Honey comb (e) Hilbert curve (f) Archimedean chords (g) Octagramspiral

3.3.6 Support material: Choosing support material will add additional structures around the model which will build up to then support the overhanging part. For assessing the maximum overhang that can be achieved without employing a support material and truncated cone was made. Typically, the semi-cone angle allowed for an overhanging product of about 45° without support material. Similar attempt has been made to find the range of truncated-cone angle in RepRap machine.

1) Creation of a CAD Model of cone with a base in “Unigraphics”, using different truncated-cone angles (5°,25°,30°,35°,40°,45°,50°,55°,60°,65°).

2) Conversion of above CAD models into STL files and imported them to the RepRap Machine and produced the components.

Some of the observations are:

a) As the truncated-cone angle is increased the staircase effect also gets increased.

b) In this machine, we can produce the cone having truncated cone angle more than 45° without using any support material (Figure 3.9).

c) Initially, 30° truncated cone angle model was found a bit faulty. Therefore, it was produced again but then also was not a satisfactory model.

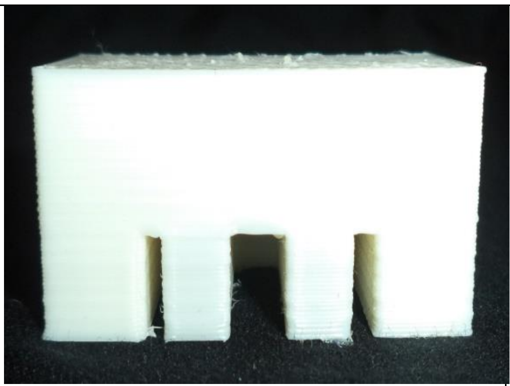
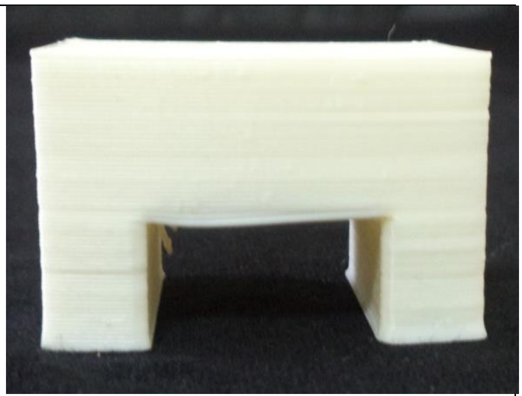
	
Component with support material	Component without support material

Figure 3.8: Parts varying support material

	
Truncated-cone of angle 30 degrees	Truncated-cone of angle 60 Degrees

Figure 3.9: Parts with different angles

4. EXPERIMENTS & RESULTS

4.1 Tensile test

Tensile tests are simple, relatively inexpensive, and fully standardised. By applying a force on a material using a uniaxial load, the reaction of the material can be readily recorded and analysed. During the tensile testing as the material is stretched until it breaks, a comprehensive tensile profile will result producing a curve showing how it reacted to the forces being applied. This curve is commonly referred to as a “Load-Extension” diagram. The load at which the material fails is of much interest on these diagrams as is the maximum load the material can withstand.

The ASTM type-4 standard, the standard for tensile properties of plastics (ASTM 638-02a) was used tensile testing of the parts made with the Rep-Rap machine.

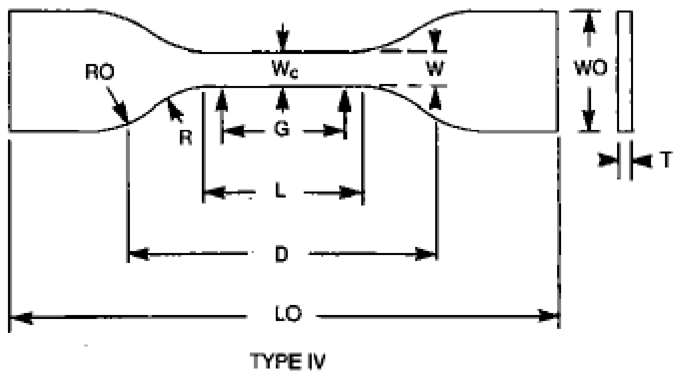


Figure 4.1: Schematic diagram of tensile specimen

Table 4.1: ASTM (type-4) dimensions

W	Width of Narrow Section	6mm (0.25)
L	Length of Narrow Section	33mm (1.30)
WO	Width Overall	19mm (0.75)
LO	Length Overall	115mm (4.5)
G	Gage Length	25mm (1.00)
D	Distance between Grips	65mm (2.5)
R	Radius of Fillet	14mm (0.56)
RO	Outer Radius	25mm (1.00)

The Figure 4.2 shows the tensile specimen produced by Rep-Rap Machine, which is a Layered Manufacturing process. For the same model with default parameters, have been produced by varying seven the fill patterns viz., Rectilinear, line, Honeycomb, Concentric, Hilbertcurve, Archimedean chords, Octagramspiral, available in slic3r software.

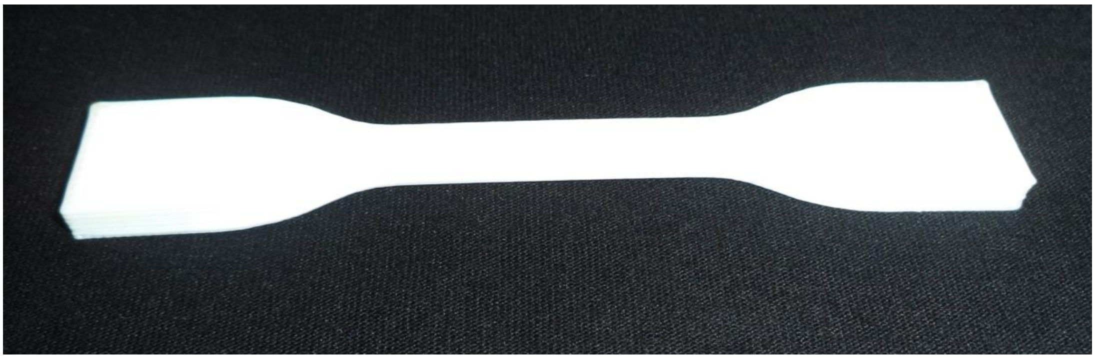


Figure 4.2: Component produced from Rep-Rap machine before testing

The numbers of specimens produced were 21 (the experiments were repeated for three specimens for each value).

For these 21 specimens, we conducted the tensile test by using the UTM machine.

4.2 Experimental Setup of UTM machine:

An Instron make UTM was used for determining the tensile properties. The following are the specifications of the machine used:

- Maker: INSTRON
- Model number: 5966
- Capacity: 10KN
- Software: Blue Hill

Figure 4.3: UTM machine setup at IITH

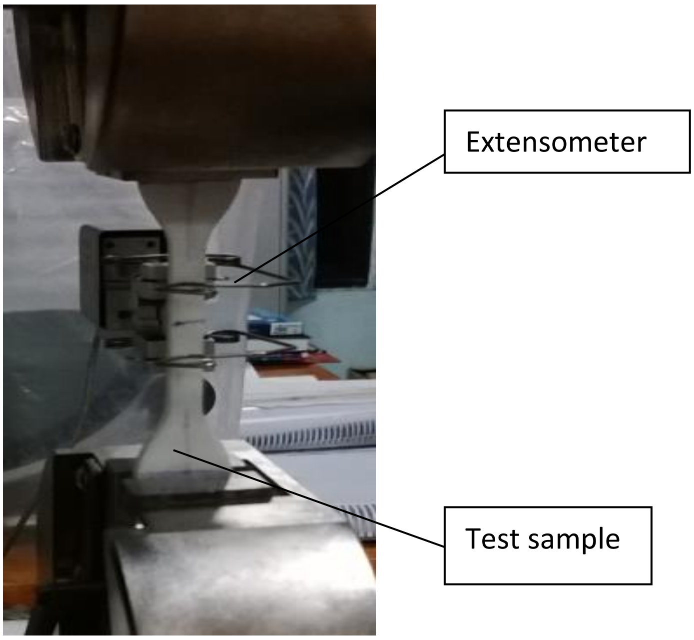


Figure 4.4: During operation

To test the properties of the test samples, the samples were loaded onto the UTM machine in tension. The load and extension data of the samples was then collected by loading the specimen. An extensometer was used to measure the strain of the samples.

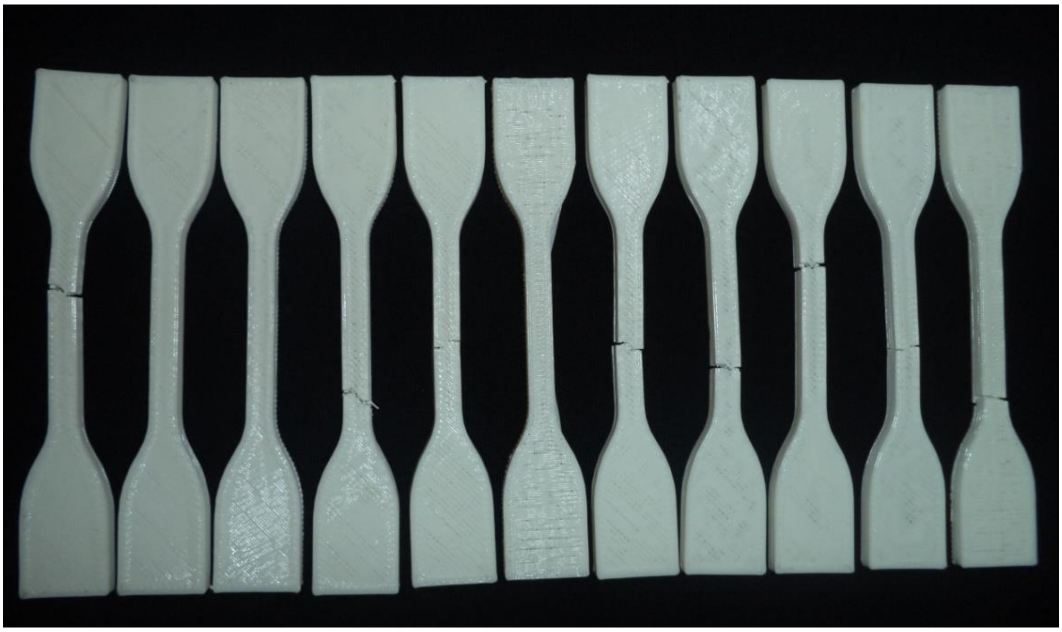


Figure 4.5: Components after Testing

4.3 Experiments:

4.3.1 Rectilinear:

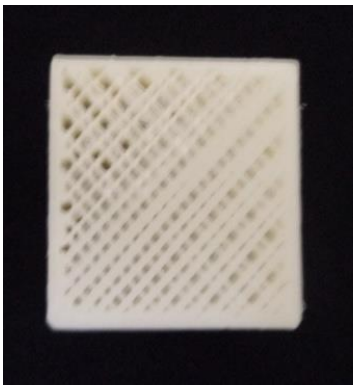


Figure 4.6: Rectilinear Fill pattern

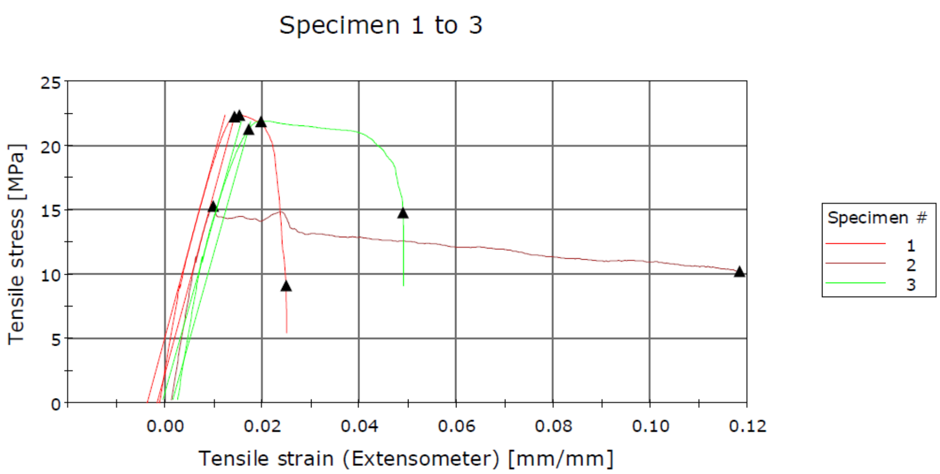


Figure 4.7: Plot of Tensile stress vs. strain (Rectilinear)

Table 4.2: Values for 3 Specimens (Rectilinear)

Serial no.	**Specimen label**	**Maximum load (N)**	**Tensile stress at max. Load (Mpa)**	**Tensile stress at Yield (zero slope) (Mpa)**	**Young's modulus (Mpa)**
1	1a	536.95	22.37	22.28	1394.12
2	1b	529.97	22.14	22.03	1369.47
3	1c	525.59	21.90	21.27	1342.31

4.3.2 Honeycomb:

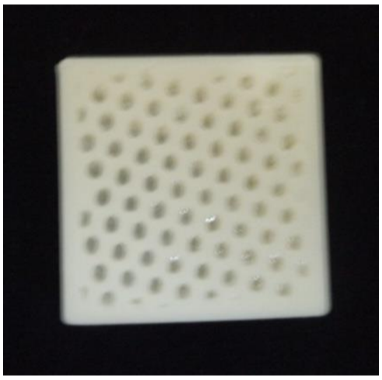


Figure 4.9: Honeycomb Fill pattern

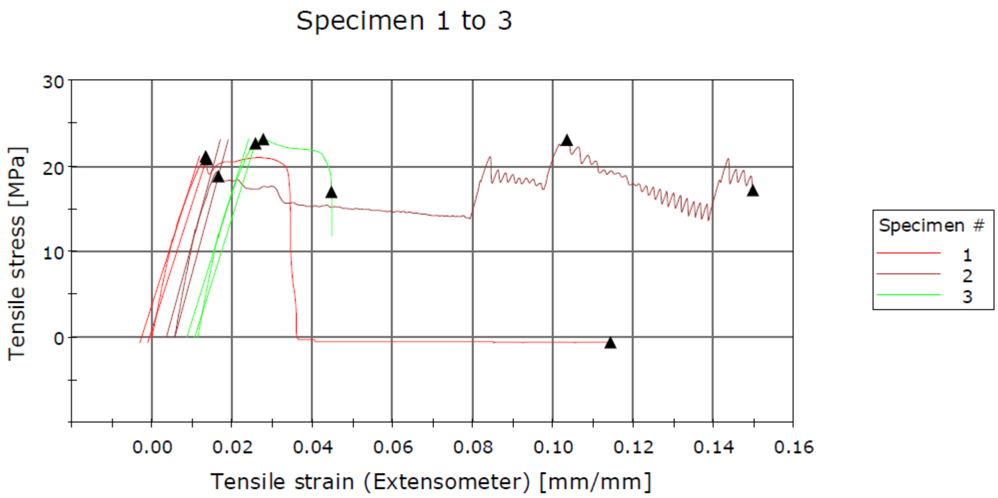


Figure 4.10: Plot of Tensile stress vs. strain (Honeycomb)

Table 4.3: Values for 3 Specimens (Honeycomb)

Serial no.	Specimen label	Maximum load (N)	Tensile stress at max. Load (Mpa)	Tensile stress at Yield (zero slope) (Mpa)	Young's modulus (Mpa)
1	2a	506.65	21.11	20.79	1457.56
2	2b	553.17	23.05	18.80	1714.95
3	2c	554.62	23.11	22.62	1501.12

4.3.3 Line:

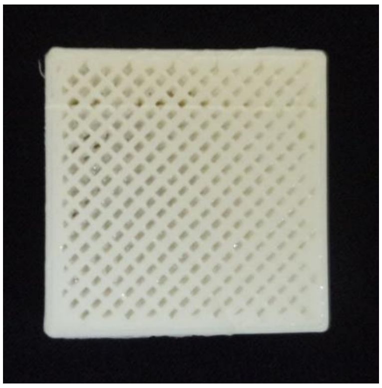


Figure 4.11: Line Fill pattern

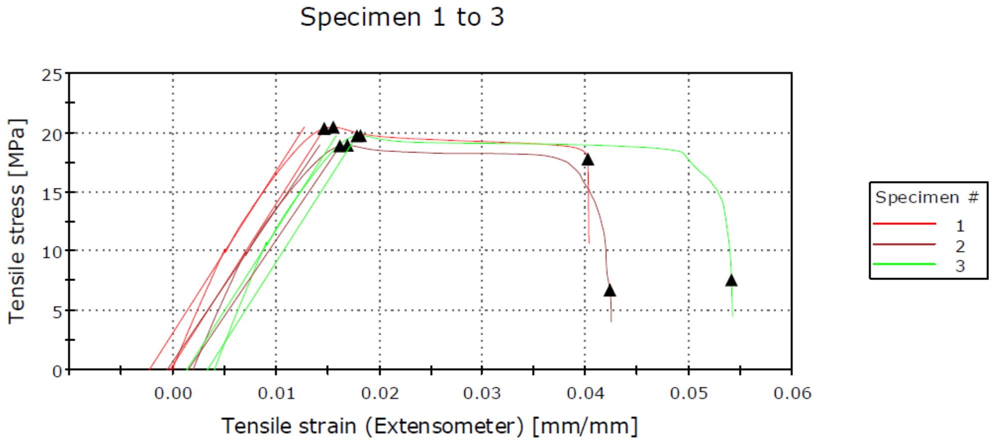


Figure 4.12: Plot of Tensile stress vs. strain (Line)

Table 4.4: Values for 3 Specimens (Line)

Serial no.	Specimen label	Maximum load (N)	Tensile stress at max. Load (Mpa)	Tensile stress at Yield (zero slope) (Mpa)	Young's modulus (Mpa)
1	3a	491.12	20.46	20.35	1359.49
2	3b	454.90	18.95	18.89	1281.35
3	3c	473.98	19.75	19.73	1362.01

4.3.4 Concentric:

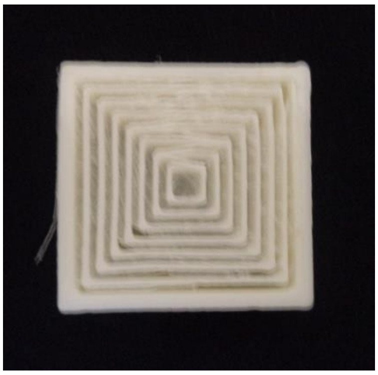


Figure 4.13: Concentric Fill pattern

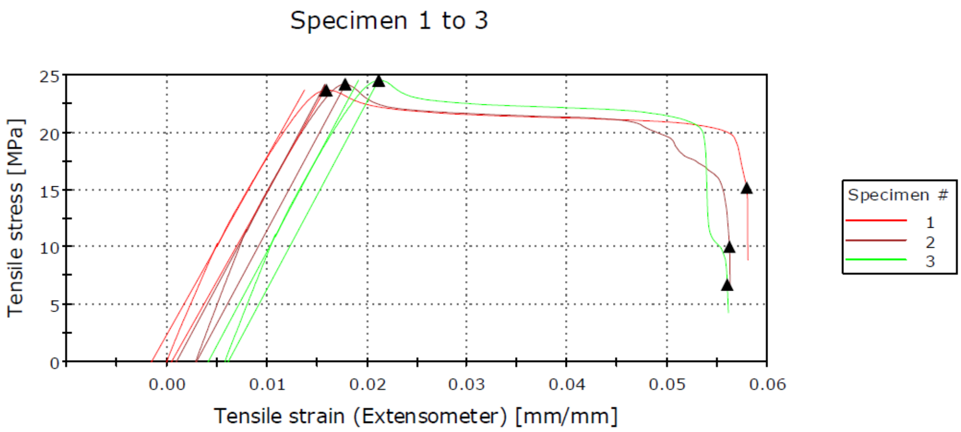


Figure 4.14: Plot of Tensile stress vs. strain (Concentric)

Table 4.5: Values for 3 Specimens (Concentric)

Serial no.	Specimen label	Maximum load (N)	Tensile stress at max. Load (Mpa)	Tensile stress at Yield (zero slope) (Mpa)	Young's modulus (Mpa)
1	4a	567.97	23.67	23.64	1548.13
2	4b	580.32	24.18	24.18	1624.43
3	4c	588.26	24.51	24.50	1632.11

4.3.5 Hilbertcurve:

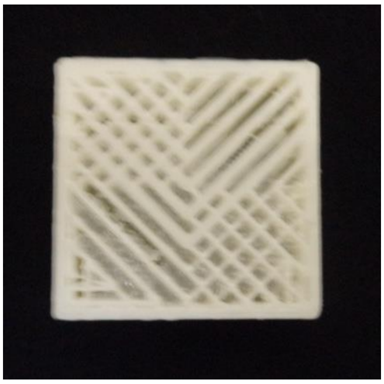


Figure 4.15: Hilbertcurve Fill pattern

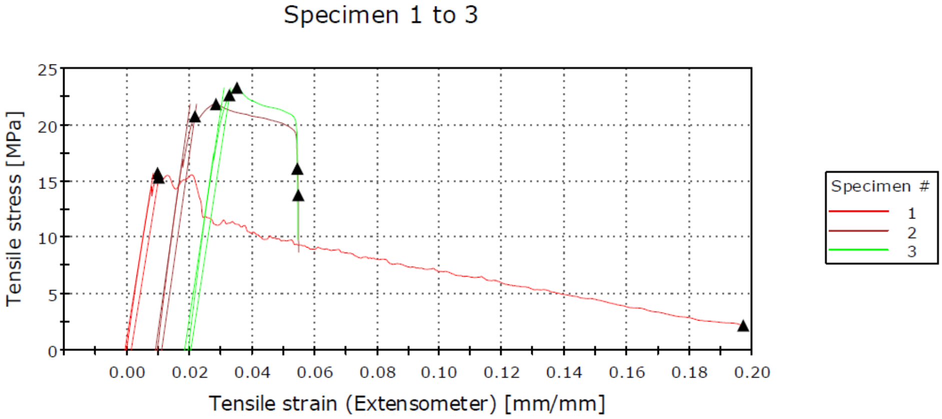


Figure 4.16: Plot of Tensile stress vs. strain (Hilbertcurve)

Table 4.6: Values for 3 Specimens (Hilbertcurve)

Serial no.	Specimen label	Maximum load (N)	Tensile stress at max. Load (Mpa)	Tensile stress at Yield (zero slope) (Mpa)	Young's modulus (Mpa)
1	5a	377.41	15.73	15.33	1729.74
2	5b	523.59	21.82	20.75	1957.93
3	5c	558.76	23.28	22.62	1834.60

4.3.6 Archimedean chord:

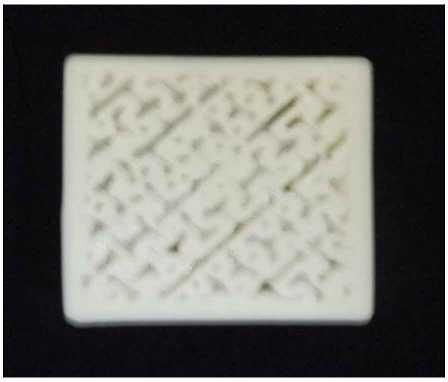


Figure 4.17: Archimedean chords Fill pattern

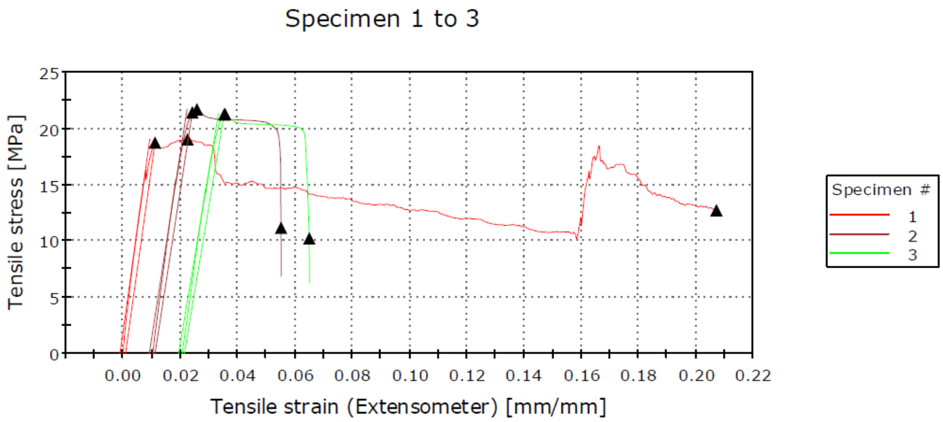


Figure 4.18: Plot of Tensile stress vs. strain (Archimedean chord)

Table 4.7: Values for 3 Specimens (Archimedean)

Serial no.	Specimen label	Maximum load (N)	Tensile stress at max. Load (Mpa)	Tensile stress at Yield (zero slope) (Mpa)	Young's modulus (Mpa)
1	6a	456.68	19.03	18.74	1823.91
2	6b	520.68	21.69	21.42	1646.69
3	6c	510.41	21.27	21.23	1532.25

4.3.7 Octagramspiral:

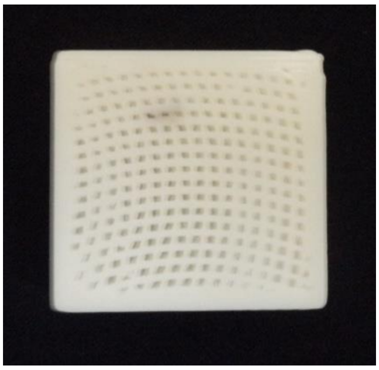


Figure 4.19: Octagramspiral Fill pattern

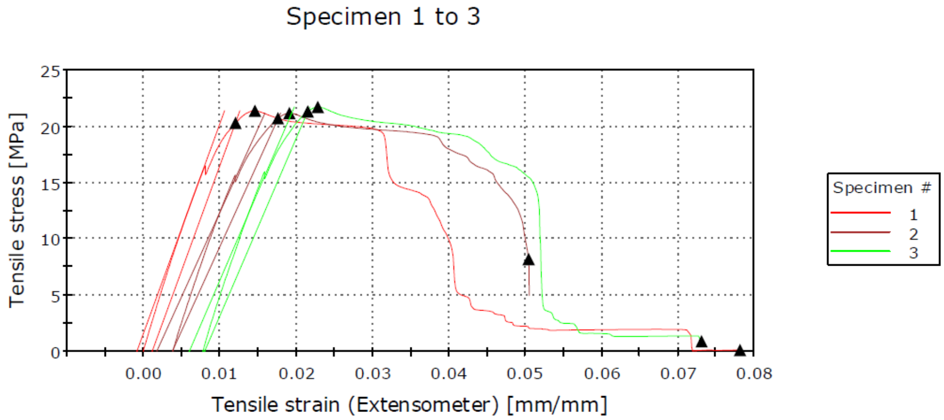


Figure 4.20: Plot of Tensile stress vs. strain (Octagram spiral)

Table 4.8: Values for 3 Specimens (Octagram)

Serial no.	Specimen label	Maximum load (N)	Tensile stress at max. Load (Mpa)	Tensile stress at Yield (zero slope) (Mpa)	Young's modulus (Mpa)
1	7a	512.87	21.37	20.30	1858.75
2	7b	507.86	21.16	20.69	1490.16
3	7c	520.87	21.70	21.31	1575.57

4.4 Summary of Experimental Results:

The following table summarizes the experimental results for various fill patterns. Figures 4.5 to 4.8 depicts the behaviour of ultimate strength, Young's modulus, maximum load and tensile stress at yield for Rectilinear, Honeycomb, Line, Concentric, Hilbertcurve, Archimedean and Octagram fill patterns.

Table 4.9: Comparison of all properties

Serial no.	Type	Average max. Load (N)	Average tensile stress at max. Load (Mpa)	Average tensile stress at Yield (zero slope) (Mpa)	Average Young's modulus (Mpa)
1	Rectilinear	530.83	22.13	21.86	1368.63
2	Honeycomb	538.14	22.42	20.73	1557.87
3	Line	473.33	19.72	19.65	1334.28
4	Concentric	578.85	24.12	24.10	1601.55
5	Hilbertcurve	486.58	20.27	19.56	1840.75
6	Archimedean	495.92	20.66	20.46	1667.61
7	Octagram	513.86	21.41	20.76	1641.49

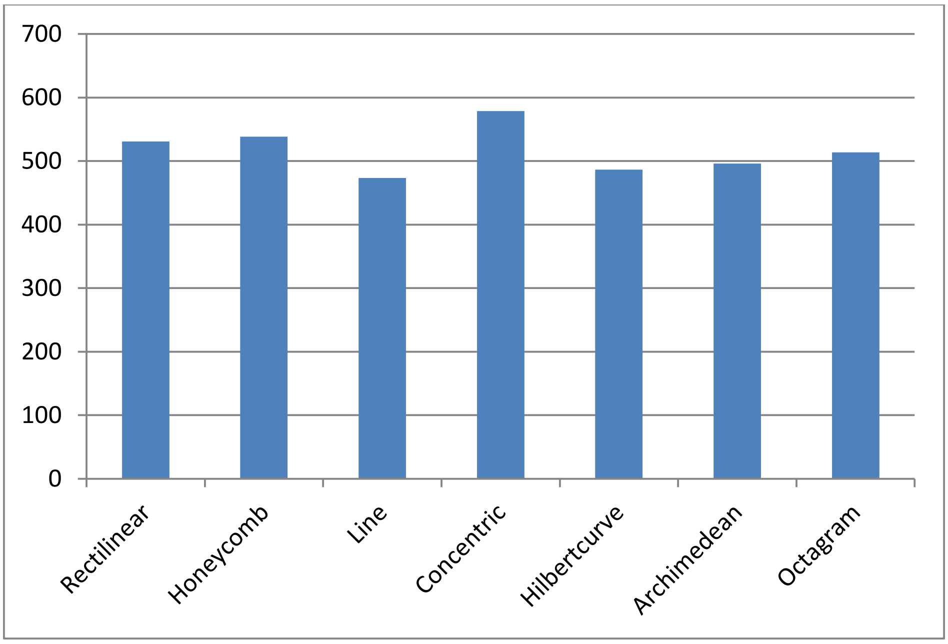


Figure 4.21: Maximum load for various fill patterns

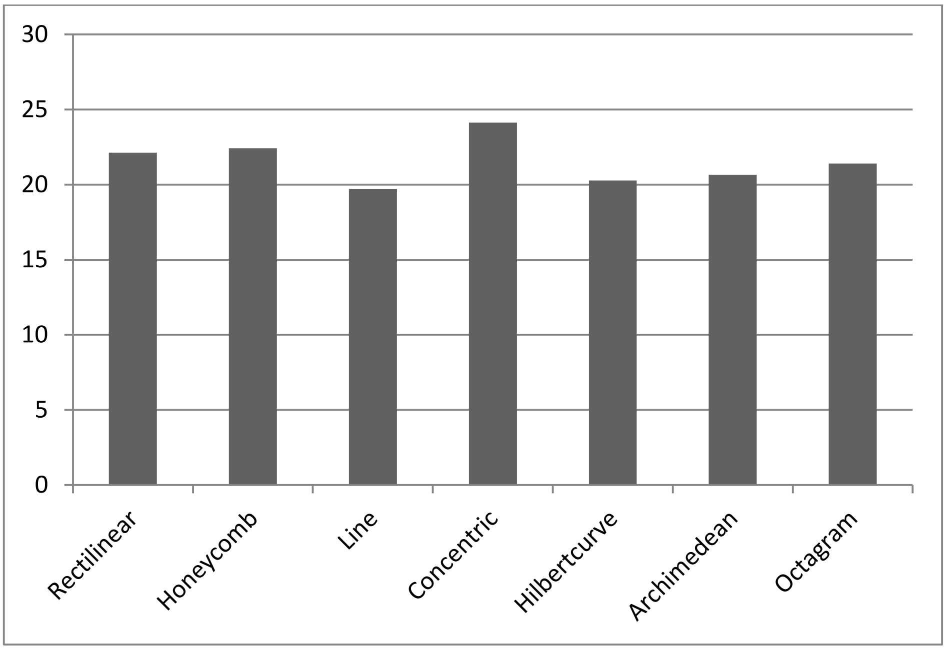


Figure 4.22: Ultimate strength for various fill patterns

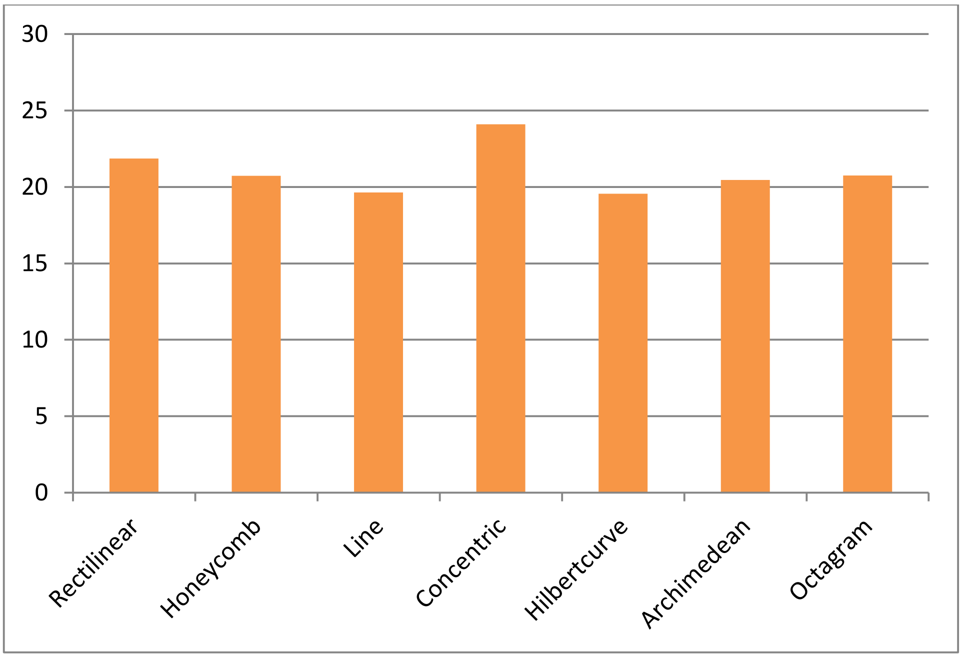


Figure 4.23: Tensile stress at yield for various fill patterns

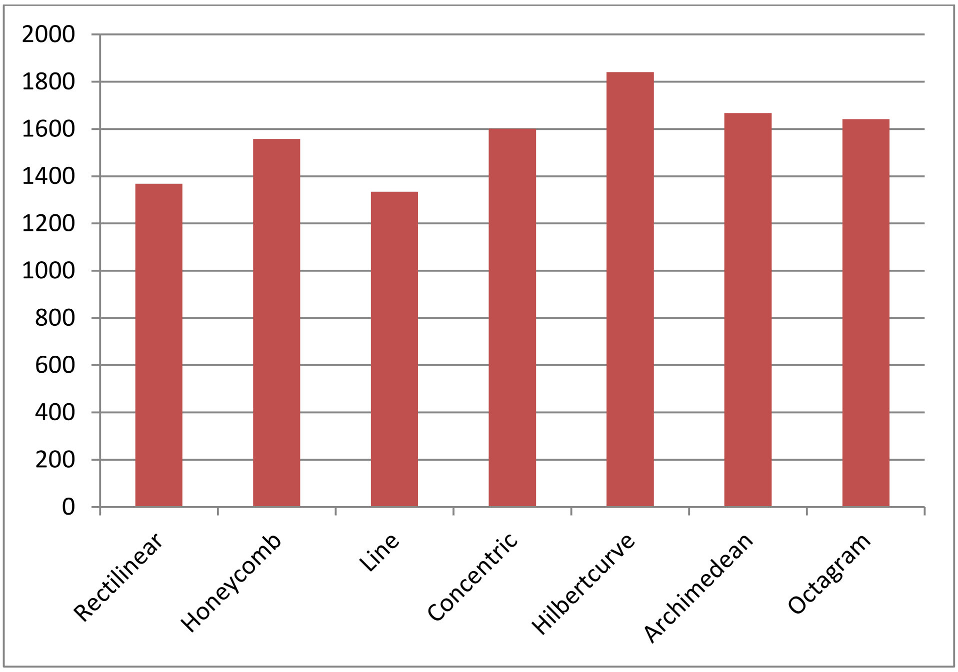


Figure 4.24: Young’s modulus for various fill patterns

5 CONCLUSIONS

5.1 Conclusion

Different types of tensile components were fabricated through FDM process and subjected the testing to find their tensile properties. As anticipated, the mechanical properties of FDM parts varied a lot for different fill patterns. The following summary will help the user in identifying the right fill pattern for a desired object:

1. **Rectilinear fill pattern**: The ultimate strength and young's modulus are 22.13 Mpa and 1368.63 Mpa respectively.
2. **Honeycomb fill pattern**: The ultimate strength and young's modulus are 22.42 Mpa and 1557.87 Mpa respectively.
3. **Line fill pattern**: The ultimate strength and young's modulus are 19.72 Mpa and 1334.28 Mpa respectively.
4. **Concentric fill pattern**: The ultimate strength and young's modulus are 24.12 Mpa and 1601.55 Mpa respectively.
5. **Hilbertcurve fill pattern**: The ultimate strength and young's modulus are 20.27 Mpa and 1840.75 Mpa respectively.
6. **Archimedean fill pattern**: The ultimate strength and young's modulus are 20.66 Mpa and 1667.61 Mpa respectively.
7. **Octagram fill pattern**: The ultimate strength and young's modulus are 21.41 Mpa and 1641.49 Mpa respectively.

On comparing the results, it was found that ultimate strength is more in concentric fill pattern (24.12 Mpa) and Young's modulus is more in Hilbertcurve fill pattern (1840.75 Mpa).

The ultimate strength was found to be in ascending order of Line, Hilbertcurve, Archimedean, Octagram, Rectilinear, Honeycomb, Concentric fill patterns respectively.

The Young's modulus was found to be in ascending order of Line, Rectilinear, Honeycomb, Concentric, Octagram, Archimedean, Hilbertcurve fill patterns respectively.

5.2 Future Scope

The current work focuses on the effect of fill patters on the mechanical properties. The build orientation also plays a major role in the mechanical behaviour of the parts and may also be explored in the future. Similarly, apart from tensile properties, other mechanical parameters like fatigue life and crack propagation can also be studied.

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